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An Investigation of Sensitive Air Jets and their Acoustical Properties

AN INVESTIGATION OF SENSITIVE AIR JETS AND THEIR ACOUSTICAL PROPERTIES

BY

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B. S. University of Chicago, 1917

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN PHYSICS

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1920

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

May 19 1920

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY RALPH DOUGLAS DOWER

ENTITLED AN INVESTIGATION OF SENSITIVE AIR JETS AND THEIR ACOUSTICAL PROPERTIES

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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________________ Final Examination*

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TABLE OF CONTENTS

I INTRODUCTION

The purpose of this investigation is to determine quantitatively some of the important properties of sensitive jets, and to test some of the conclusions drawn from theory. A sensitive jet consists of a fluid, either gaseous or liquid, issuing from a small orifice under pressure. If the shape of the orifice is sufficiently regular and the pressure properly adjusted, the jet will be straight and of uniform cross section for some distance out from the orifice, and terminate quite abruptly in a "flare" or "break". This break may be caused to occur nearer the orifice by the action of sounds of the proper pitch and intensity. Because of its response to such sounds the jet is said to be sensitive.

II HISTORICAL SKETCH

The class of phenomenon known as "Sound-Sensitive Jets" was discovered by Professor Leconte in 1858 while attending a concert in the United States. Some illuminating gas jets which happened to be burning at the right pressure were noticed to shorten in height for certain musical sounds. His account of these observations[1] led Tyndall[2] to perform an extended series of experiments, with some success in determining the nature and characteristics of not only ignited gas jets but unignited and liquid jets.[3] He studied sensitive flames issuing from orifices whose cross sections were circular, elliptical, flat and irregular, and the effects on these of varying the cross section of the orifice, the pressure, the kind of gas, the pitch and intensity of the disturbing sound, and the point of sound attack.

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1. Phil.Mag., 1858, p 235.
2. Tyndall, Sound., p 250.
3. Tyndall, Sound., p 270.

His observations were mostly qualitative, yet of considerable value in explaining the action of such jets.

He found that any increase in pressure above the critical pressure caused the jet to break and flare at a point nearer the orifice and concluded that since sound produced the same effect it must be due to the change in pressure in a sound wave, setting up longitudinal vibrations in the jet. Lord Rayleigh disproved this theory, as will be shown later.

Tyndall's experiments with unignited gas jets showed them to be similar to flames, though much simpler and with a greater range of sensitiveness. The simplicity is due to the uniformity of temperature and density, thus leaving only the dynamic properties of the jet to account for its action. This is well illustrated by an air jet in still air. To make such a jet visible he introduced some smoke particles and used strong illumination.

Lord Rayleigh[4] made an extensive mathematical analysis of this class of phenomenon, and verified many of his conclusions by experiment. His theory which we will consider presently explains roughly much that was previously obscure.

In 1918 Dr. Ray E. Hall of Chicago, Illinois, invented a device called an "air jet relay" which makes use of the sound sensitiveness of such air jets in controlling an electrical circuit. A jet without sound disturbance is adjusted so that it breaks immediately after passing through the center of an electrically heated coil of fine platinum wire. The effect of a sound is to cause the break to occur lower, thus enveloping the coil in a cooling blast of air, which changes the resistance and therefore the current in the circuit,

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4. Lord Rayleigh, Theory of Sound, Vol.II, p 400.

which in turn operates a balanced electromagnetic relay. The usefulness of this device and its dependence on the characteristics of sensitive jets for its operation makes a further study of the theory of jets of importance.

III THEORY

Beginning with the two dimensional case of a vortex sheet separating two layers having different velocities, Lord Rayleigh developed the equations of motion, then by imposing the proper limiting conditions he showed that these applied approximately to sensitive jets. That is, he showed analytically that the sensitivity of a jet depended neither on friction nor longitudinal vibrations but on the inherent instability of a sheet separating regions of different velocities, which is, however, somewhat modified by assuming a viscous rather than a non-viscous fluid. From this theory he deduced the following facts and substantiated them by experimental proof: a jet is most sensitive to sound at its base; the vortex motion on the surface of the jet resulting from its velocity procudes differences of pressure on opposite sides, thus producing (non-periodically) the same effect as sound; the lateral motion of any part of the jet thus produced increases exponentially and on reaching a critical value, disrupts the entire jet; and that this instability increases with the velocity.

The expression which he derived giving the amplitude h of the sinuosity at the distance x from the orifice, imposed on the jet by a disturbance at the origin, is

$$h = He^{\pm\sqrt{kl}\ k\ vt} \cos k(x - klvt).$$

For t=0 and x=0, we have h=H, the amplitude of the initial disturbance. 2l is the thickness of the jet, v, the velocity. The disturbance involves x and t only through the factors e^{ikx} and e^{int}. Thus, the manner in which a state of motion, which in the hydrodynamic

treatment is stable, will depart from the steady state, once a disturbance is introduced, is given.

A rigorous interpretation of this equation would lead one to conclude that, since the frequency of the disturbance is a function of K, the greater the frequency the more marked would be the departure from the steady state, which experience shows is not the case. Lord Rayleigh shows this discrepancy to be due to the assumption that the velocity gradient is discontinuous. Assuming that this discontinuity does not exist, but rather that the velocity transition occurs in a layer of finite thickness, he shows that any disturbance which tends to impress a wave length on the vortex sheet comparable with 21 will not be augmented. For a cylindrical jet this criterion of stability may be expressed as the ratio of that critical wavelength λ, and the diameter d of the jet, or (λ/d).

By the aid of this approximate theory and an experimental determination of the critical constants, the behavior of a jet may be predicted.

IV EXPERIMENTAL WORK

The preceding discussion shows that the various phenomena of a sensitive jet are only partly understood and that the information available has been gathered from "cut and try" methods rather than by systematic work suggested by the theory of the subject. The present investigation has been guided by the latter plan with the expectation of contributing additional information from quantitative experiments concerning these constants and the general behavior of the jet.

Photograph I shows the arrangement of apparatus with the jet in operation. Fig. I shows a simplified schematic diagram. The air

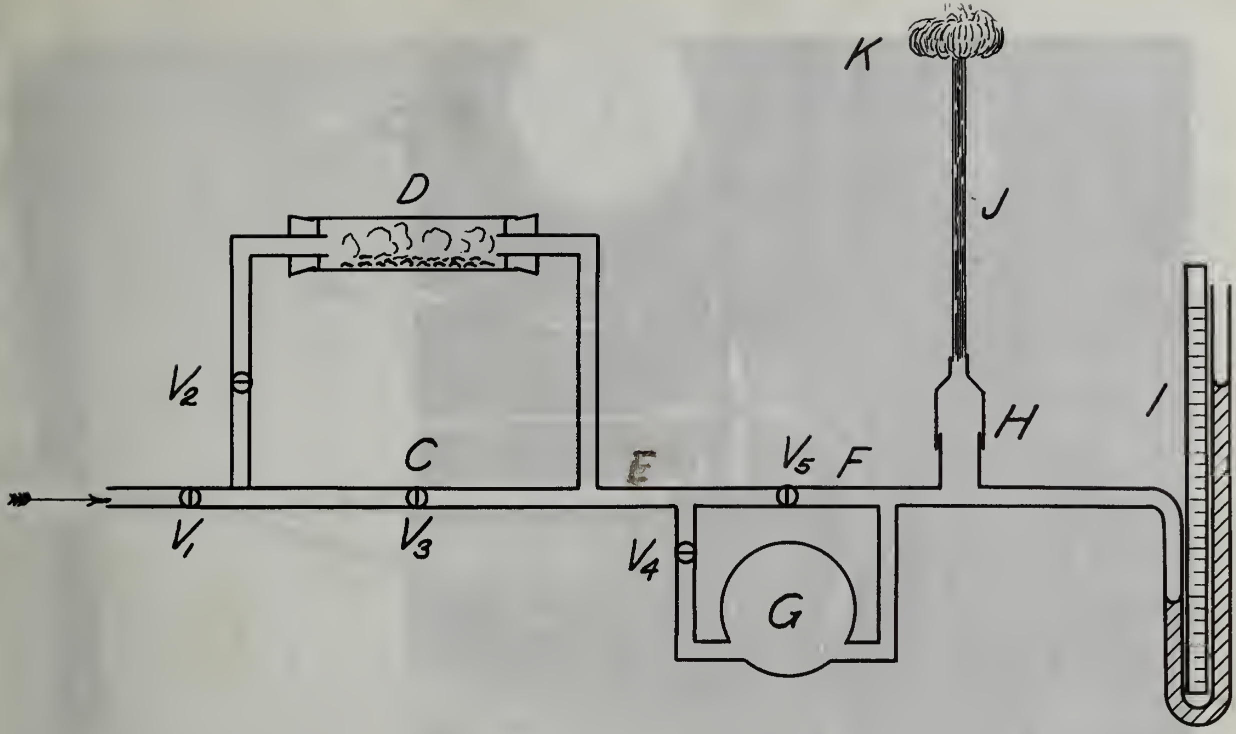


Figure I

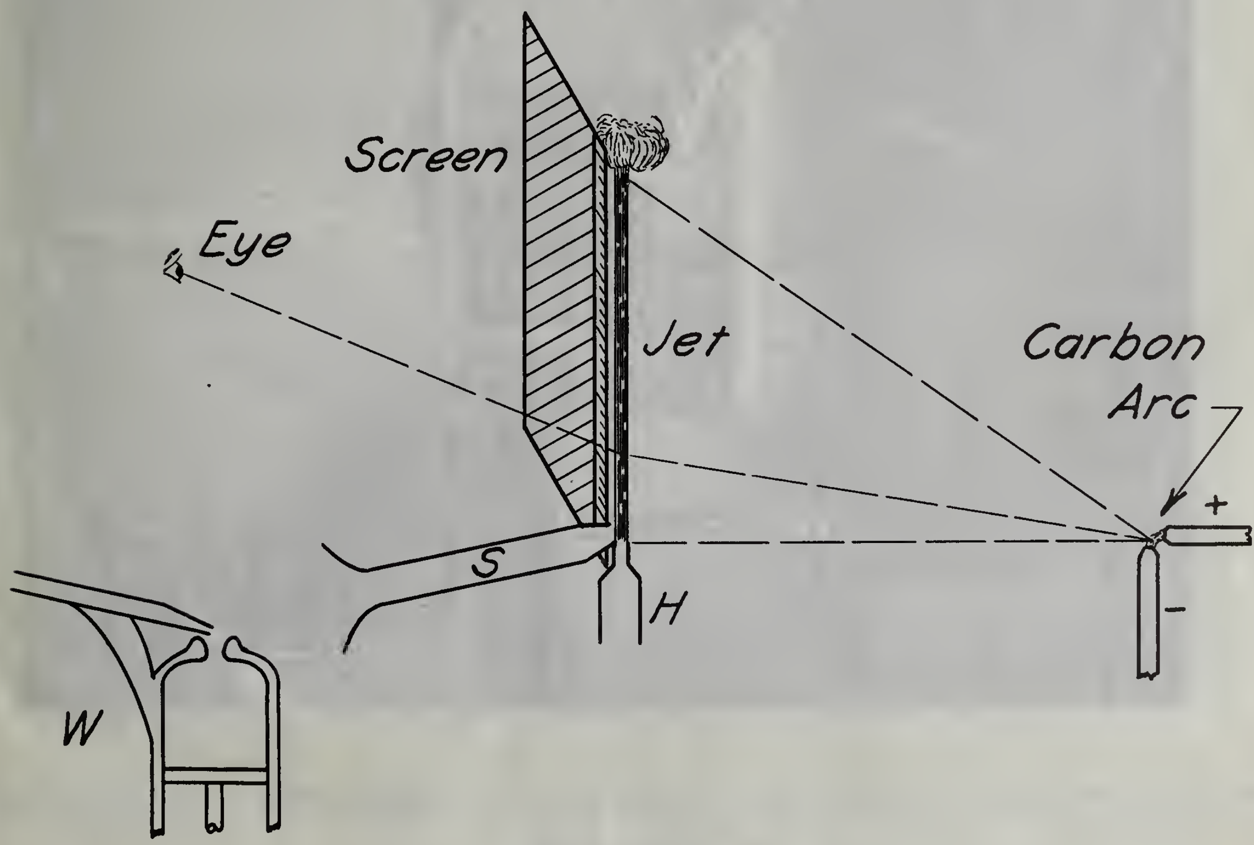


Figure II

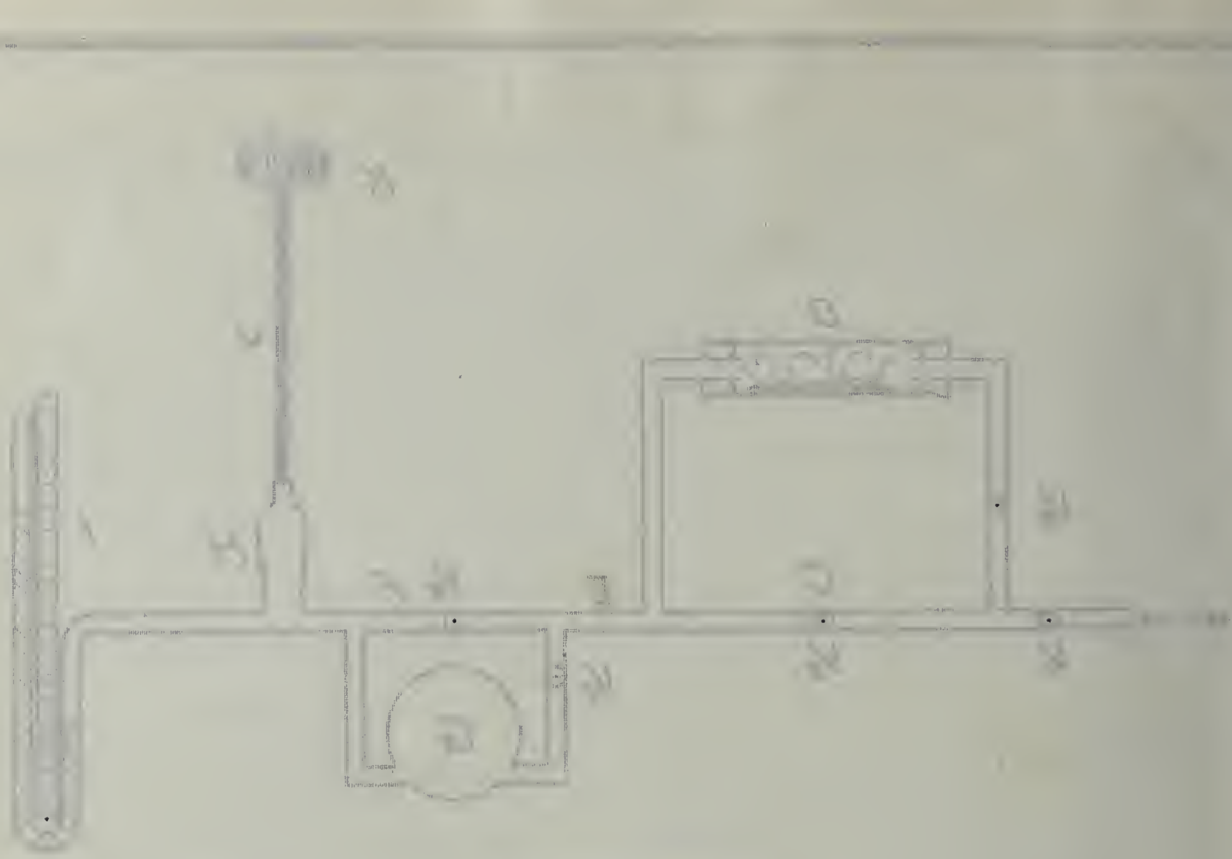
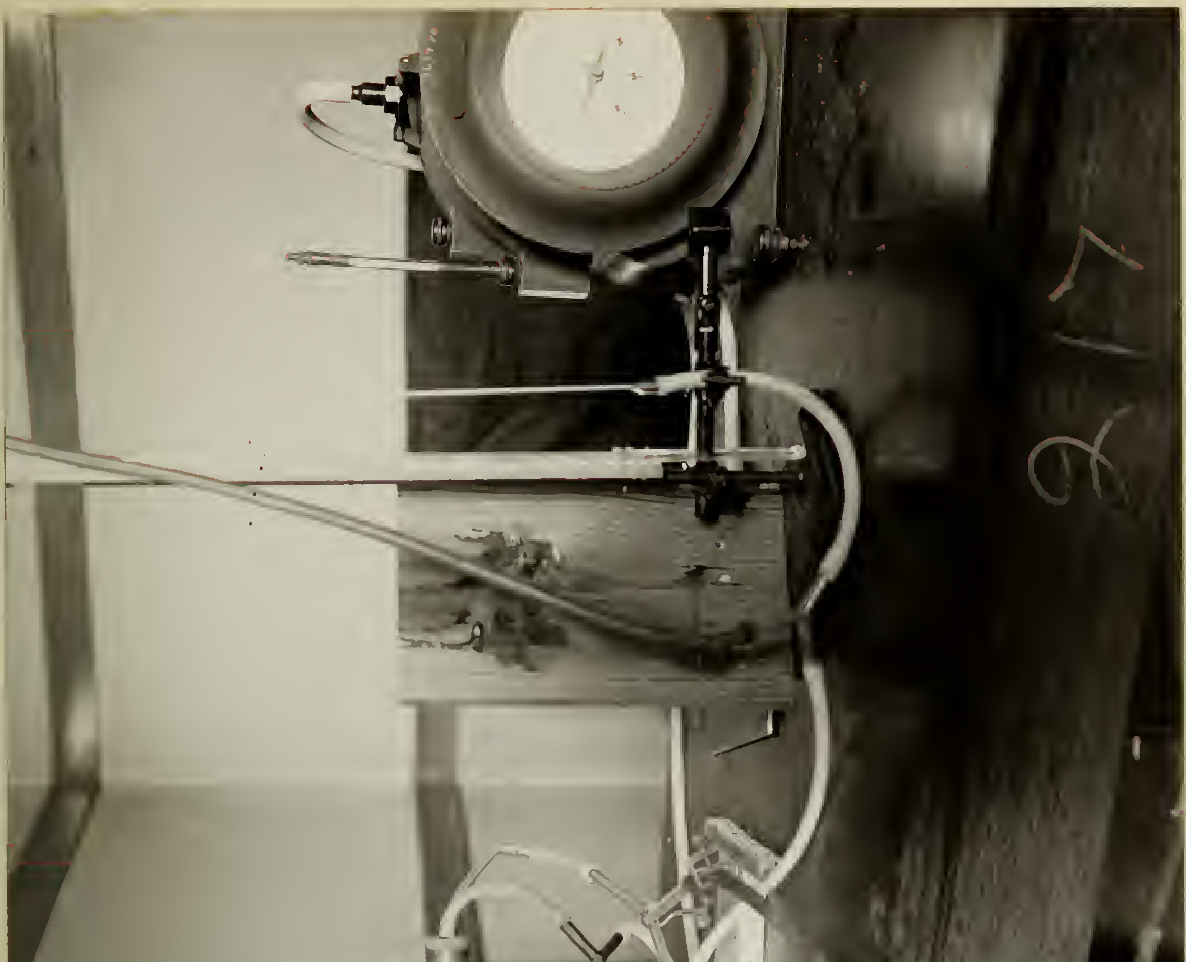
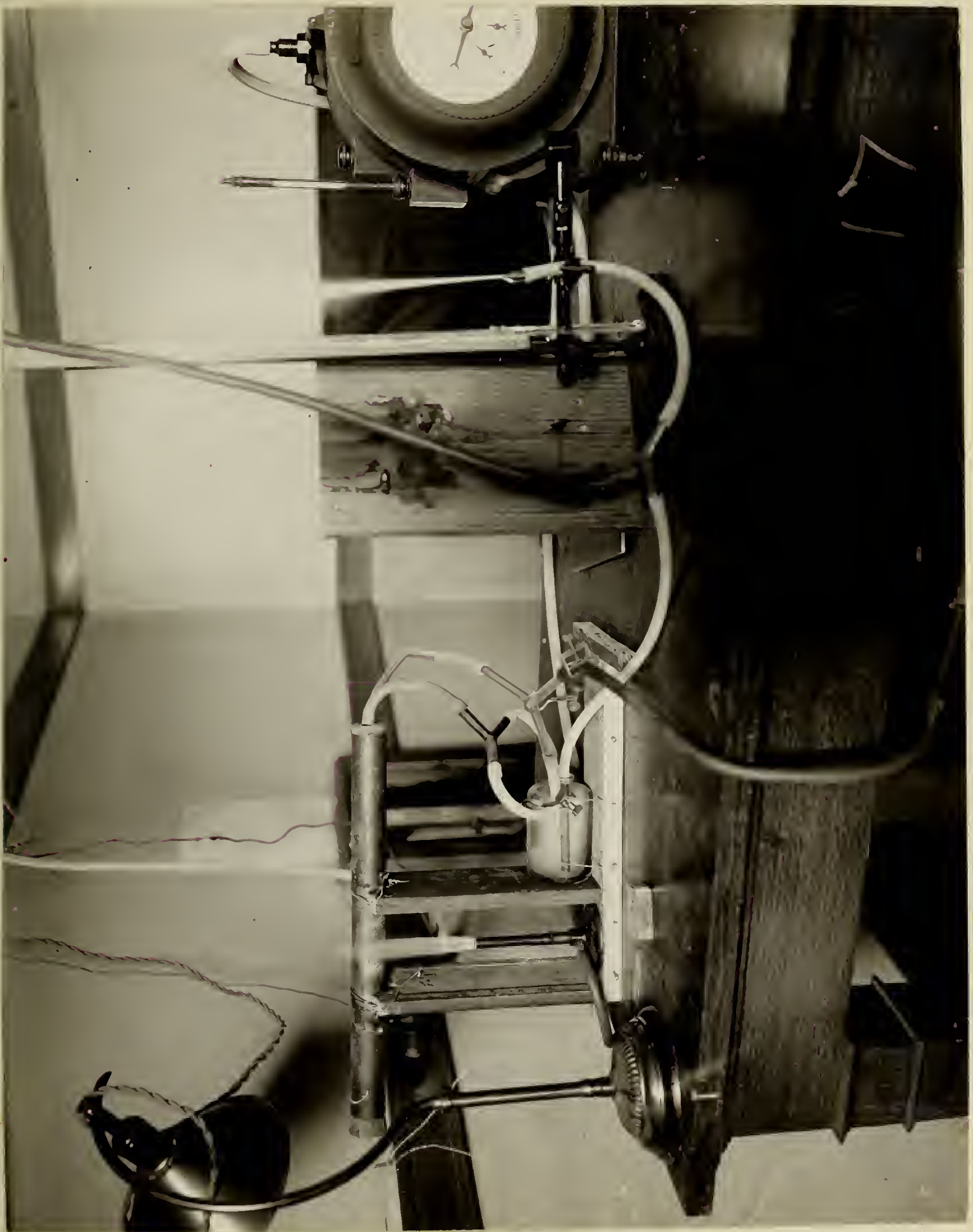


Figure I

Figure II



PHOTOGRAPH I. Arrangement of Apparatus Showing the Low Pressure Jet.



PHOTOGRAPH II. Arrangement of Apparatus Showing the High Pressure Jet

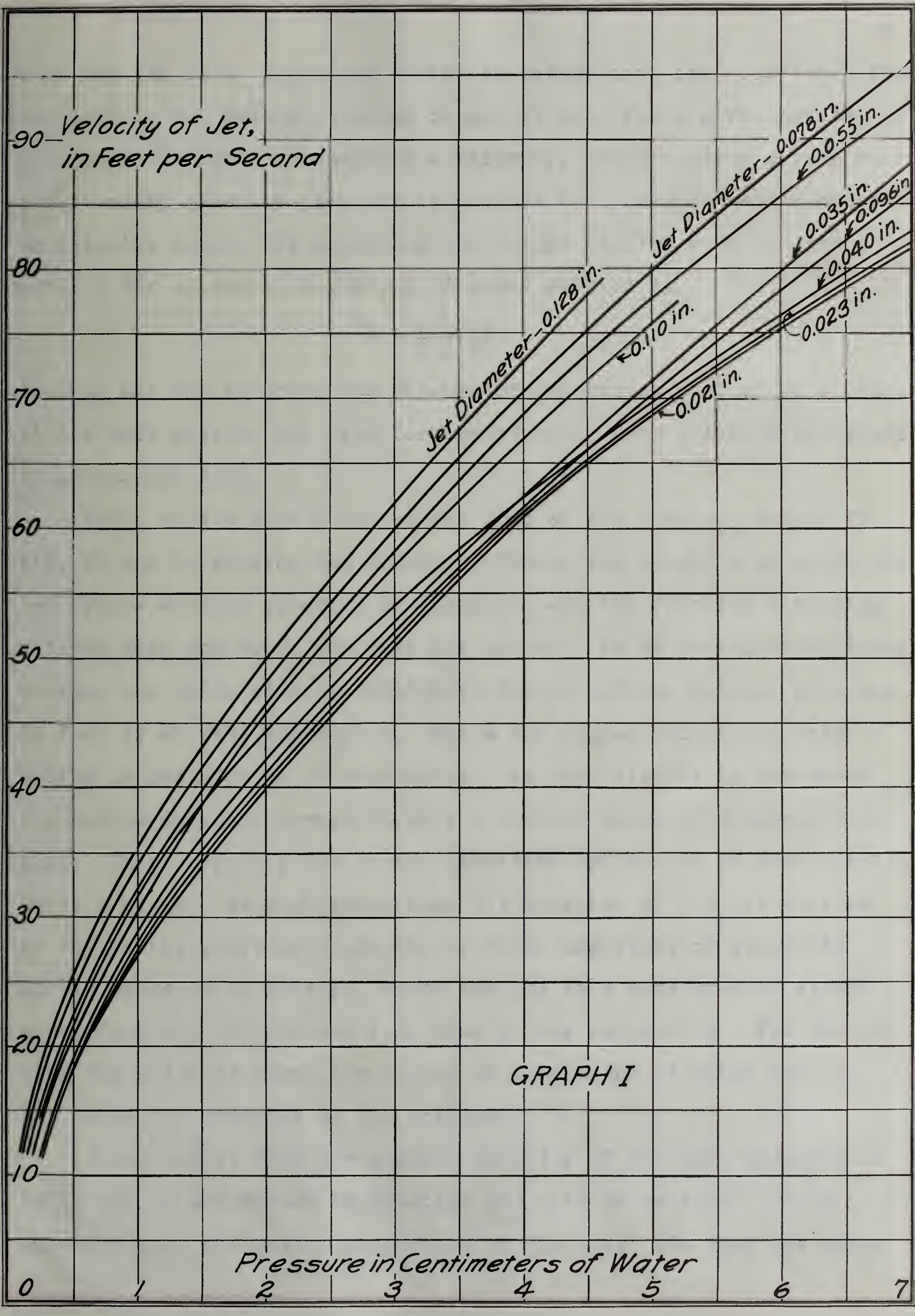
under a steady pressure enters at valve V_1 and may pass either through a smoke producing chamber D or direct through C to E, where again it may pass through the gas meter G or direct through F and V_5 to the nozzle H. From the nozzle H the air issues in a uniform jet J and terminates in an abrupt break K.

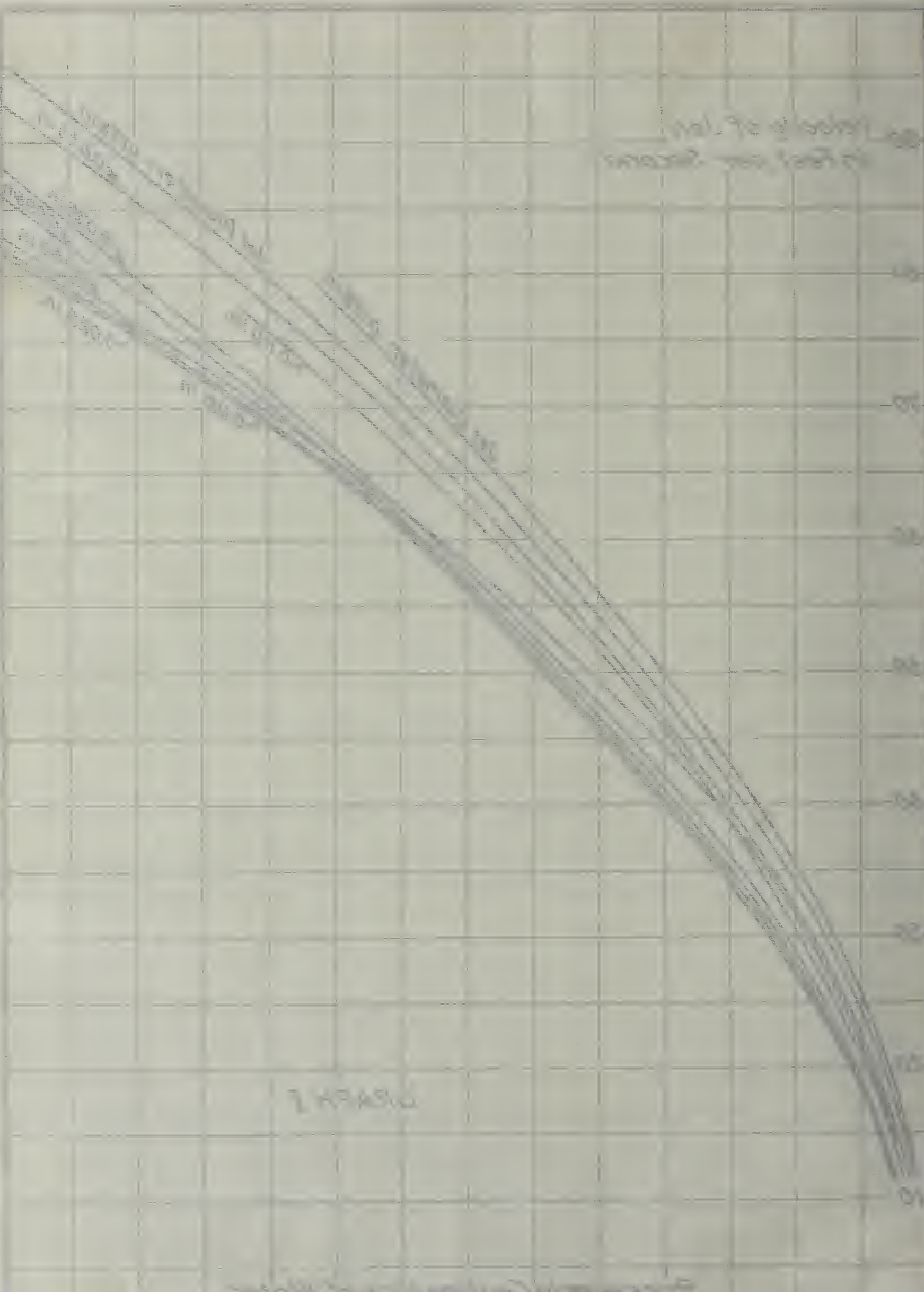
Fig. II illustrates the manner in which the jet is illuminated. The air passing through D carries smoke particles which are capable of diffracting a beam of light through a small angle. The source of illumination is a carbon arc with condensing lenses. By placing the jet between the eye and the arc and slightly to one side of the line joining the two the jet is made to appear brighter than its background when the room is dark and the arc inclosed. An opaque screen is placed near the jet to shade the eye from the direct rays and also to furnish a scale on which the position of the break may be noted.

The sound is generated by W, either a tone variator or, for high pitches, a Galton whistle. The sound may reach the jet directly or through the sound tube S.

The nozzle H is of considerable importance, since its dimensions partly determine the characteristics of the jet. Many variations in these dimensions are possible, and produce quite different effects. For instance, a jet issuing from a narrow rectangular orifice is sensitive only on the flat sides. A short nozzle causes the jet to whistle as one does with the lips. A nozzle slightly cut away on one side makes the jet most sensitive on that side. However, for simplicity a cylindrical orifice was decided upon with a length of about five times the diameter. A series of nine such nozzles was made, ranging from 0.0205 to 0.1280 inch in diameter.

An inspection of Lord Rayleigh's formula shows that the velocity


Velocity of Jet, in Feet per Second
90
80
70
60
50
40
30
20
10
Jet Diameter-0.078 in.
0.55 in.
0.035 in.
0.096 in.
0.040 in.
0.023 in.
Jet Diameter-0.128 in.
0.110 in.
0.021 in.
GRAPH I
Pressure in Centimeters of Water
0
1
2
3
4
5
6
7


GRAPH J

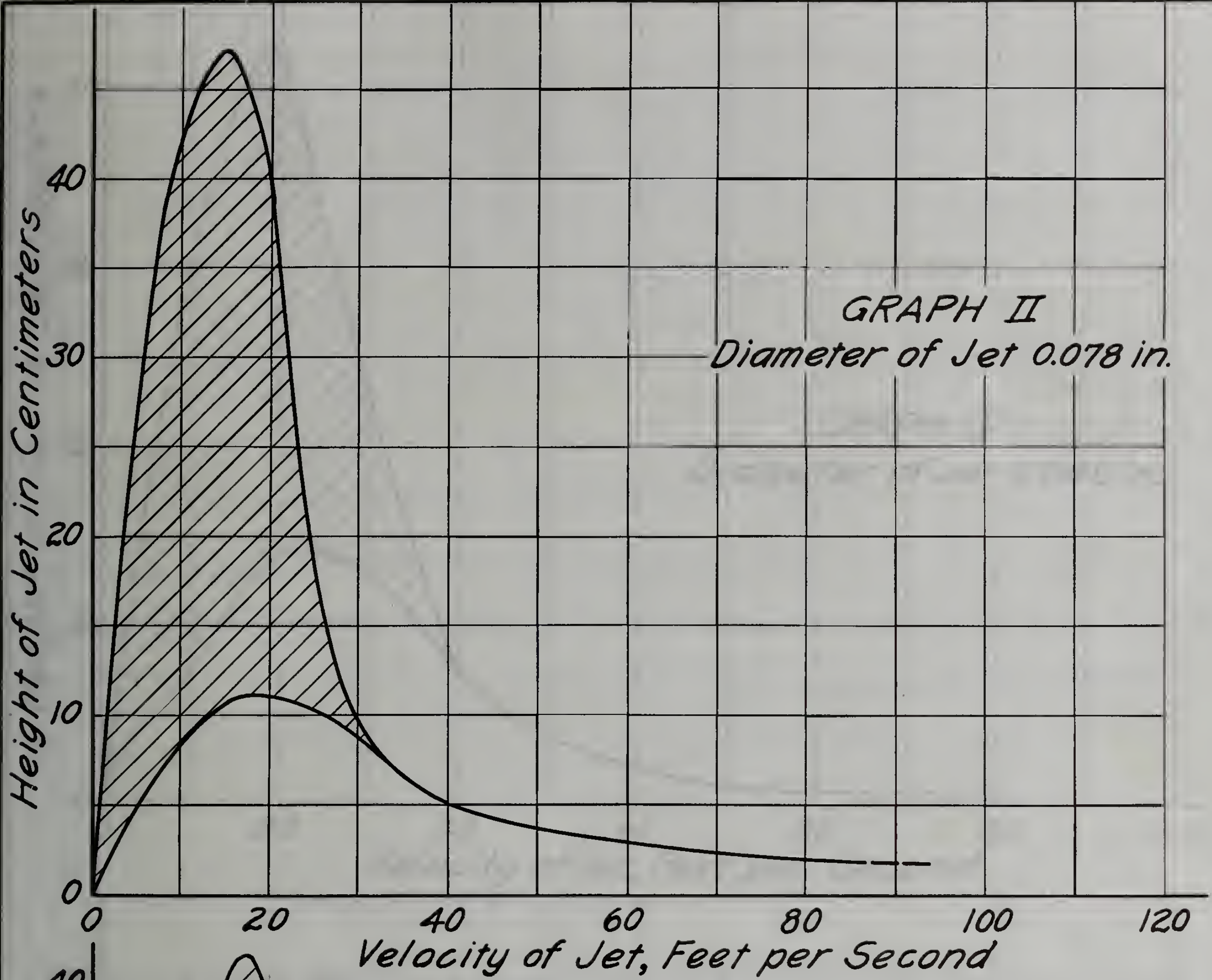
V of the jet is an important factor in determining its behavior. The velocity is not easily measured directly, but, for a given nozzle, to each pressure there corresponds a velocity, hence a curve giving this relationship makes it possible to observe the pressure and transform to velocity later. By measuring the volume of flow with the gas meter G for a time t, for a jet of cross section A,

$$V = \frac{\text{volume}}{A \times t} .$$

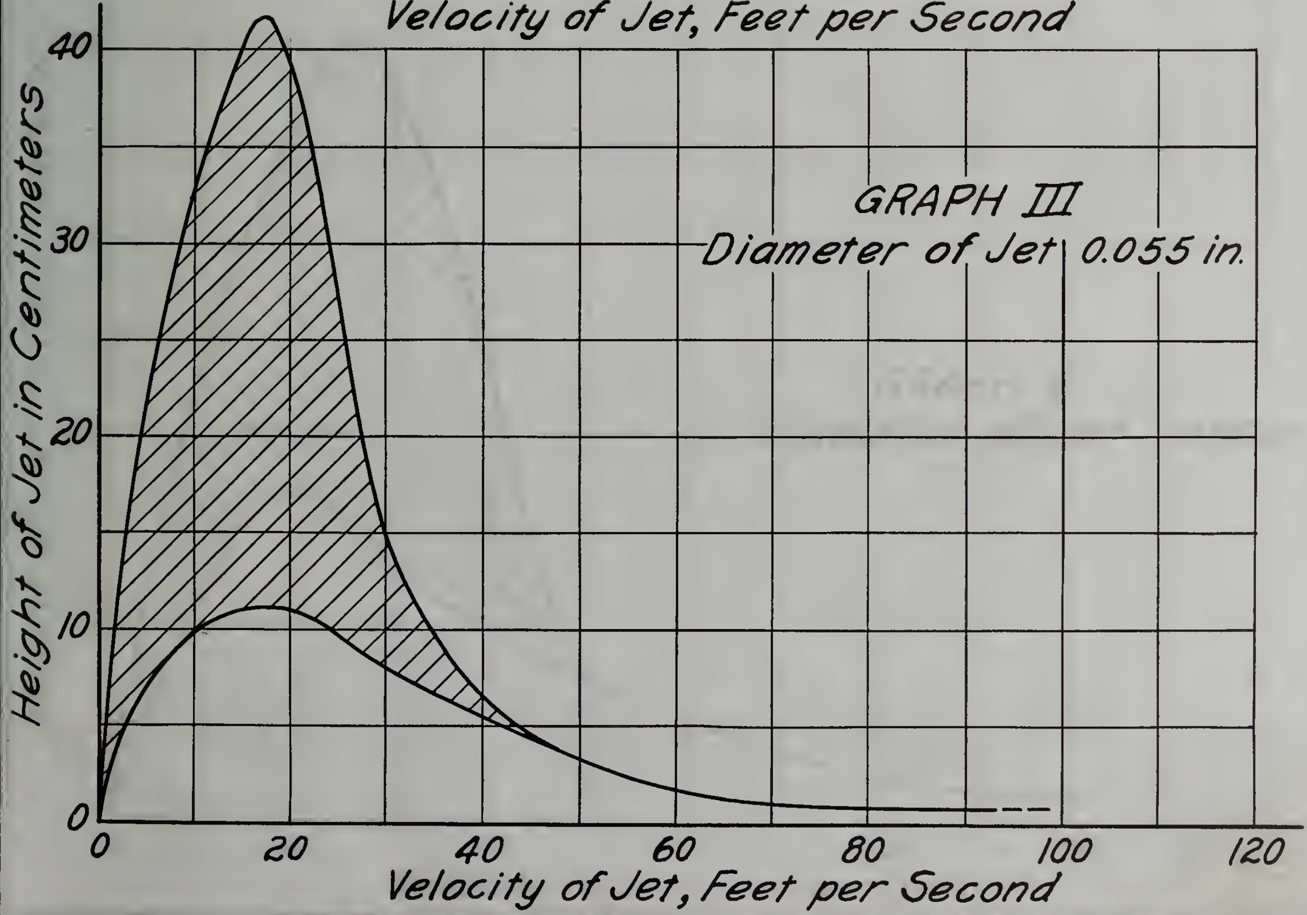
In this way the velocity was calculated and curves plotted (See Graph I) for each nozzle, and used for transforming from pressure to volume in subsequent data.

Next, curves were obtained for four of the nozzles, Graphs II, III, IV and V, showing the relation between the height x at which the jet breaks without external disturbance, and the velocity v ranging between zero and about 100 feet per second. As is indicated by these curves, the value of x is indefinite for velocities between zero and 30 feet or 40 feet per second, while for higher velocities this height is definite to .5 centimeter. As the velocity is increased the curves approach asymptotically a minimum value of x larger than zero. This is partly due to the arbitrary definition of what constitutes a break. At high velocities the momentum of the jet carries it beyond the position where the critical amplitude of sinuosity should cause it to disrupt, which results in a more gradual divergence from the cylindrical form than at low velocities. For simplicity the point of break was chosen as that point at which the jet had twice the diameter of the orifice.

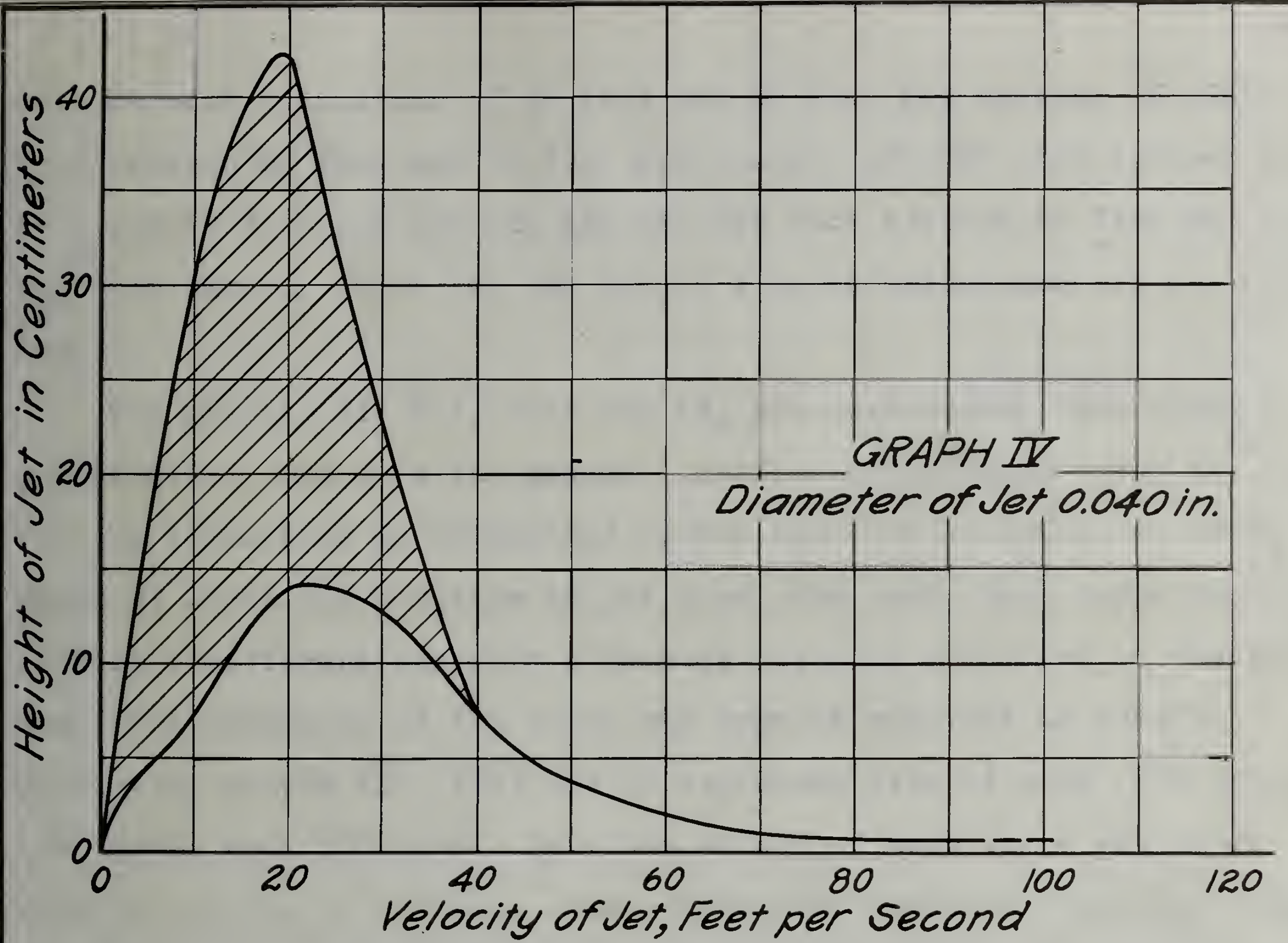
These curves show the general behavior of the jet, undisturbed by sound, as determined by velocity and size of orifice. It is apparent that the useful properties of the size .078 inch jet exist

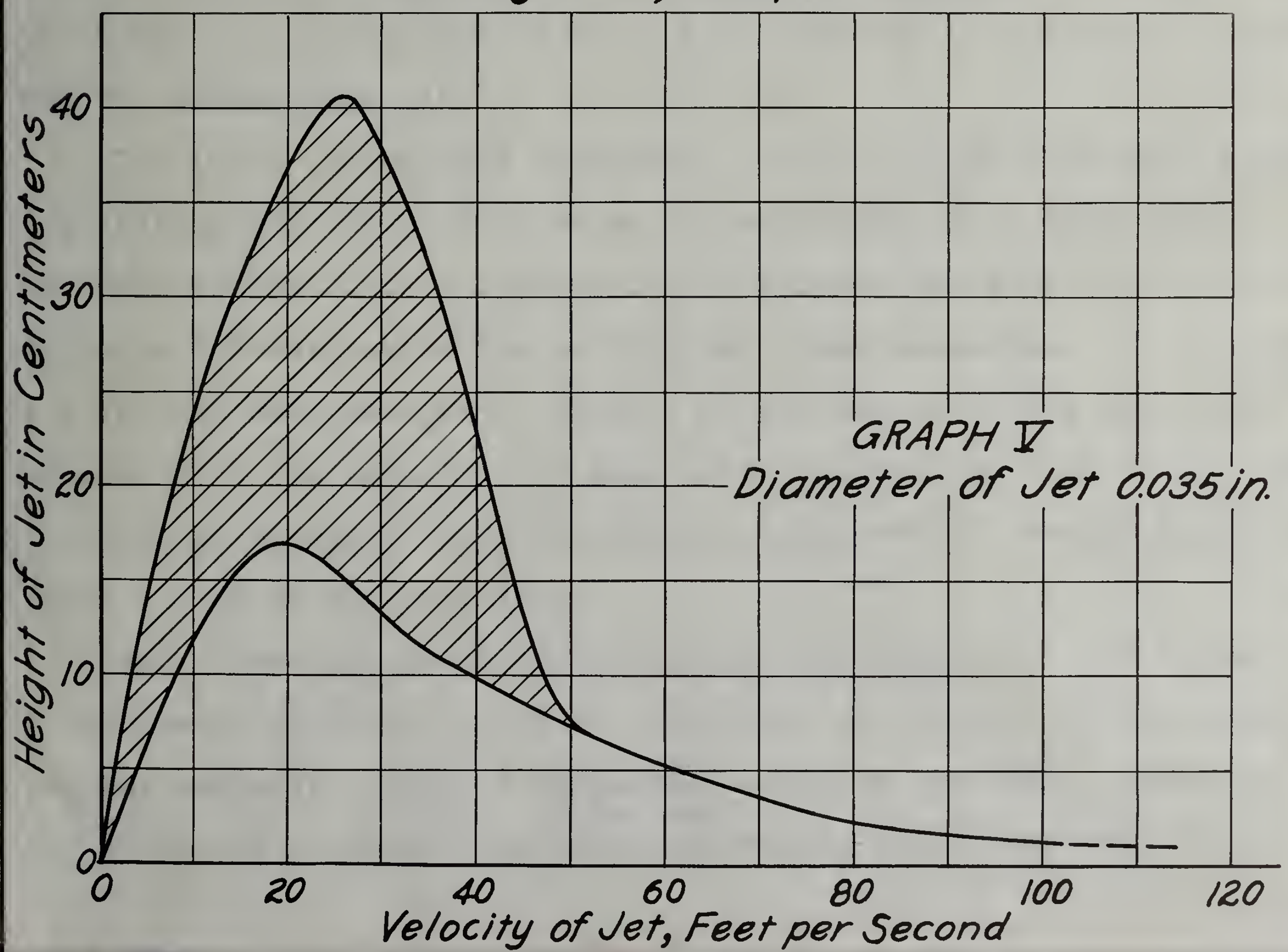


GRAPH II
Diameter of Jet 0.078 in.
Height of Jet in Centimeters
Velocity of Jet, Feet per Second
0
10
20
30
40
0
20
40
60
80
100
120



GRAPH III
Diameter of Jet 0.055 in.
Height of Jet in Centimeters
Velocity of Jet, Feet per Second
0
10
20
30
40
0
20
40
60
80
100
120


GRAPH IV
Diameter of Jet 0.040 in.
Height of Jet in Centimeters
Velocity of Jet, Feet per Second
0
10
20
30
40
0
20
40
60
80
100
120

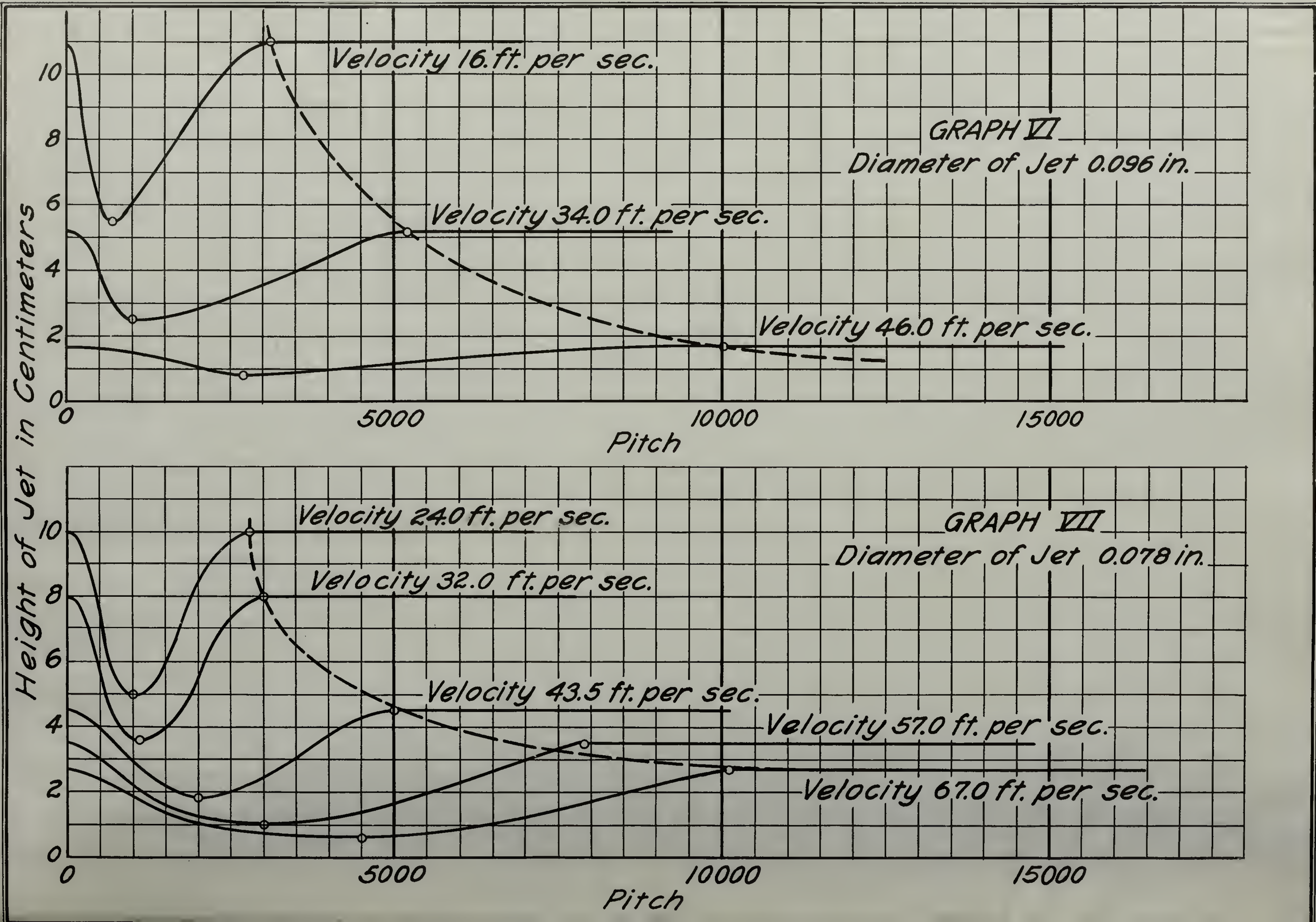

GRAPH V
Diameter of Jet 0.035 in.
Height of Jet in Centimeters
Velocity of Jet, Feet per Second
0
10
20
30
40
0
20
40
60
80
100
120

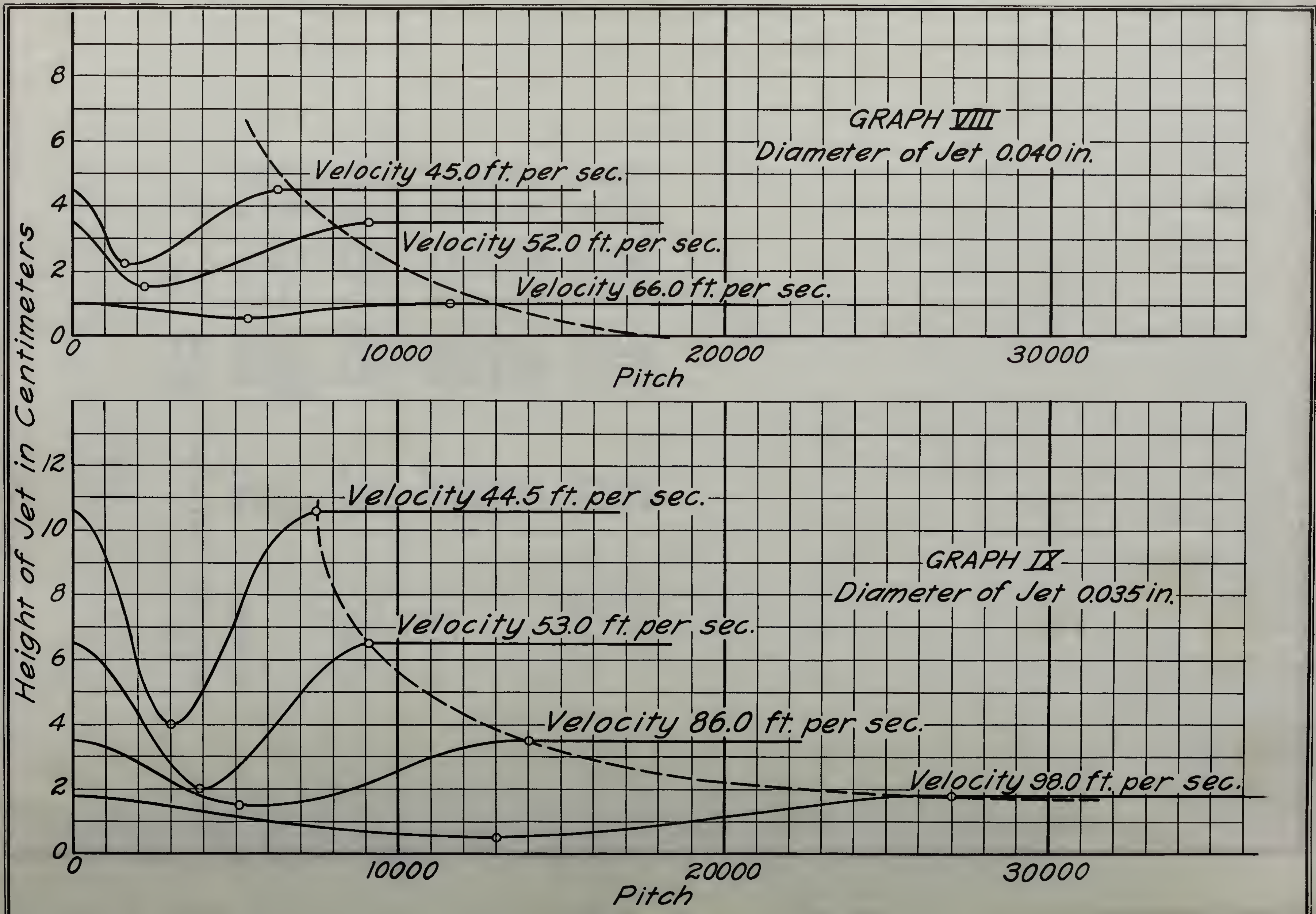
only between velocities of 30 feet and 50 feet per second; of .055 inch between 50 feet and 70 feet per second; of .040 inch between 55 feet and 70 feet per second; and of .035 inch between 60 feet and 90 feet per second. That is, the height x is definite, and not a minimum.

The graphs VI, VII, VIII and IX, are more descriptive than quantitative, and show the general behavior of different jets at various velocities as determined by the pitch of a disturbing sound. Graph VI shows the behavior of jet size .096 inch, each curve representing a different velocity with x as ordinate and pitch as abscissae. The intensity of the sound was kept as constant as possible. Similarly, graphs VII, VIII and IX represent jets of size .078 inch, .040 inch, and .035 inch. Only two points of each curve are known with any degree of accuracy, the pitch which produces a minimum value of x, and the upper pitch at which x is restored to its normal value for the undisturbed jet.

The latter points are of special interest since they afford data for testing the ratio of diameter to wavelength, d/λ, which Lord Rayleigh showed to be a criterion of the upper limit of sensitivity. In Table I these ratios are calculated. They range from 1.5 to about 4.1 for the data obtained. It will be noticed that this ratio increases with the velocity for each jet, and with the size of jet, yet is constant enough to indicate that his analysis is correct to a first degree of approximation.

From these graphs the relationships between any of the three independent variables, velocity, diameter, and pitch, and their dependent variable, either x or $\frac{dx}{d(v,d,p)}$, may be obtained. Other information may be derived by imposing certain conditions on one or


GRAPH VI
Diameter of Jet 0.096 in.
Velocity 16. ft. per sec.
Velocity 34.0 ft. per sec.
Velocity 46.0 ft. per sec.
GRAPH VII
Diameter of Jet 0.078 in.
Velocity 24.0 ft. per sec.
Velocity 32.0 ft. per sec.
Velocity 43.5 ft. per sec.
Velocity 57.0 ft. per sec.
Velocity 67.0 ft. per sec.
Height of Jet in Centimeters
Pitch
0
5000
10000
15000
0
2
4
6
8
10



Height of Jet in Centimeters
GRAPH VIII
Diameter of Jet 0.040 in.
Velocity 45.0 ft. per sec.
Velocity 52.0 ft. per sec.
Velocity 66.0 ft. per sec.
0
2
4
6
8
0
10000
20000
30000
Pitch
GRAPH IX
Diameter of Jet 0.035 in.
Velocity 44.5 ft. per sec.
Velocity 53.0 ft. per sec.
Velocity 86.0 ft. per sec.
Velocity 98.0 ft. per sec.
0
2
4
6
8
10
12
0
10000
20000
30000
Pitch

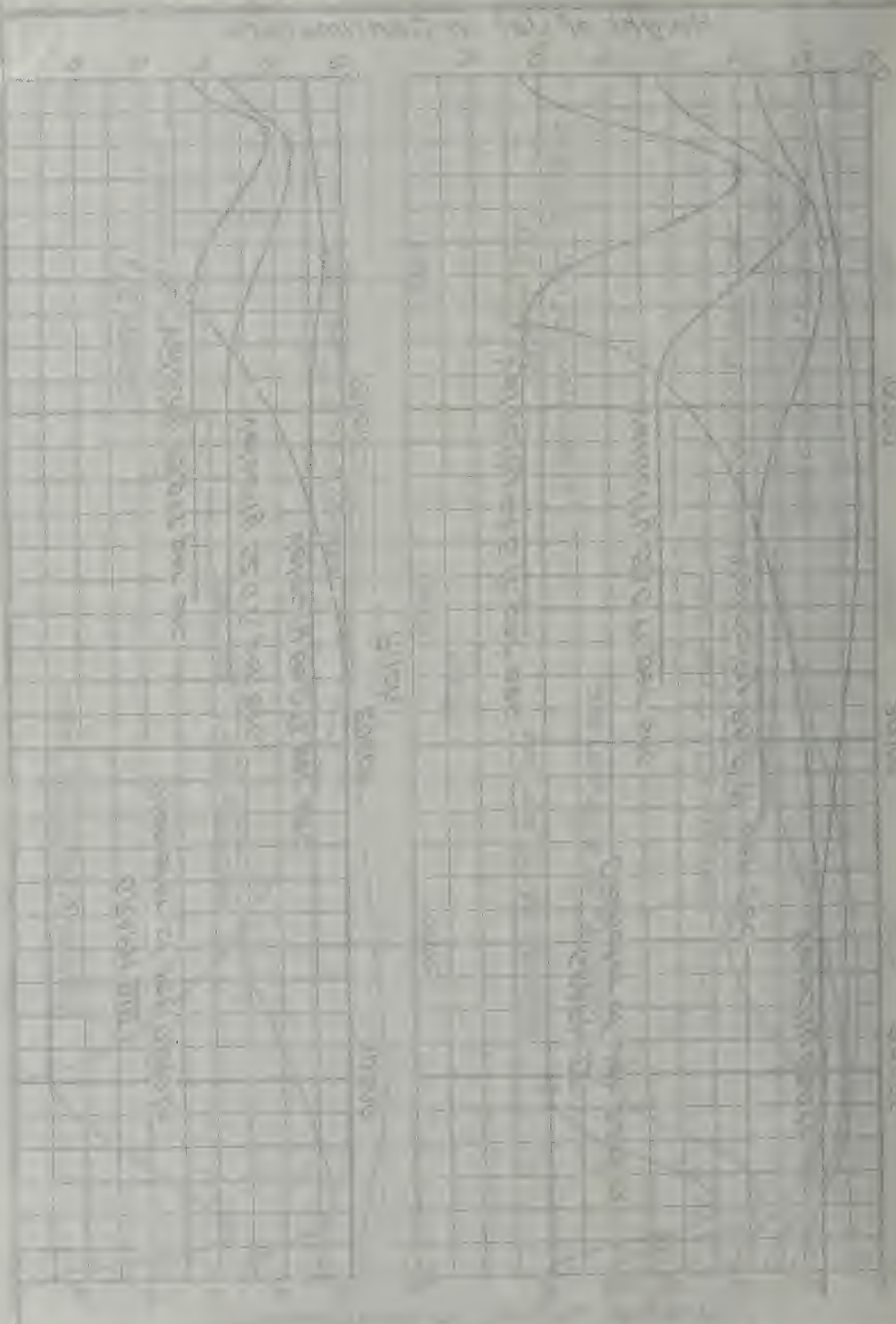


TABLE I

Jet Diameter	Velocity	Upper Pitch	Jet λ	d/λ
0.0348"	530"	7500	0.071"	1.56
	650	9200	0.071	1.56
	1030	20600	0.050	2.17
	1200	27500	0.044	2.50
0.0400"	530"	6340	0.084"	1.49
	630	9200	0.069	1.81
	870	11750	0.074	1.70
0.0785"	180"	1500	0.120"	2.04
	290	2640	0.110	2.22
	396	2740	0.145	1.81
	500	4850	0.103	2.38
	690	8250	0.084	2.94
	820	10300	0.080	3.00
0.0960"	205"	2100	0.097"	3.12
	325	3140	0.104	2.86
	425	5160	0.082	3.70
	555	7850	0.071	4.16

more of the variables, such as, pitch as a function of v to make x a minimum.

It would be very desirable to know these graphs for a wide range in the intensity of the disturbing sound, but such information could not be obtained in the present experiments with sufficient accuracy to make it of any value. It was found, however, that an increase of intensity extended the range of pitch to which the jet is sensitive, and increased the effect of the sound in lowering the value of x.

V CONCLUSION

The results of this investigation fall naturally into three groups, first, quantitative information concerning the properties of air jets, undisturbed by sound, as determined by the size of the orifice and the velocity of flow, shown in Graphs II, III, IV and V; second, the accustical properties of these jets as determined by pitch alone, other factors being kept constant, as shown in Graphs VI, VII, VIII and IX; and third, a comparison of the values of the critical ratio d/λ in these latter curves. Of these three groups the first and second represent observed facts, while the third is an attempt to interpret these facts and therefore requires further consideration.

It was pointed out in Lord Rayleigh's theory that a jet becomes insensitive to sounds that tend to impress wavelengths on it short in comparison with its diameter. If we consider the fact that the point of greatest sensitivity is at the base of the jet, one possible explanation of the decrease in sensitivity immediately suggests itself; namely, the effect produced by one half cycle of a sound wave does not travel far enough from the orifice to escape the opposing effect of the following half cycle; thus the sound neutralizes its effect

and the disturbance is not maintained. This was found to be partly true by making the area of sound attack very small and noting an increased sensitivity for high pitches. This does not fully explain the matter, however. It is probable that the vortices set up by high pitches are too small in comparison with the diameter of the jet to disrupt the motion, thus leaving the natural irregularities of lower frequencies to determine the position of the break.

It is to be expected that some particular pitch or small range of pitches should be most effective in causing an early break in the jet, hence this point needs no further discussion. Almost equally simple is the explanation of the insensitivity of a jet to very low pitches. In this case the slow lateral vibrations approach too closely the steady state, and are equivalent to a gradual change of direction of flow of the jet in still air.

In conclusion the author wishes to thank Professor F. R. Watson for his interest and inspiration in this work, and Professor A.P. Carman for the facilities of the laboratory.